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# Generation of Energy from Sugarcane Bagasse by Thermal Treatment

**B. R. Stanmore**

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**Abstract** The worldwide harvest of sugarcane for sucrose production represents a major agricultural industry, with approximately Mt 1500 produced annually. The cane yields about 13.5% of its weight as sugar, together with an equal amount (dry weight) of fibrous bagasse as waste. The bagasse, which is predominantly cellulose, is burned at the mills to generate steam for sugar processing. The global drive towards renewable energy has seen bagasse recognised as a large resource of readily-available fuel which could be better utilised to generate electricity. This review examines current methods of burning the bagasse for steam generation, and also the possibilities for steam gasification to produce a biogas suitable for combustion in gas turbines.

**Keywords** Energy · Sugarcane · Bagasse · Thermal treatment

## Introduction

The worldwide production of sugar cane in 2008 was estimated to be 1557 Mt [29]. The major producer was Brazil at 514 Mt, followed by India (356 Mt), China (106), and Thailand (64). Each tonne of cane is estimated to produce 130 kg of dry bagasse, giving a world supply of 200 million tonnes per annum. The specific energy of this material is about 19 GJ $t^{-1}$, which represents a potential global energy source of $3.8 \times 10^9$ Gigajoules. If converted to electricity at an efficiency of 20%, it would supply $200 \times 10^6$ MWh per annum, meeting the total electrical power needs of a country like Australia. Of course much of the bagasse generated is consumed during the separation and refining of sugar product. In addition, its use is complicated by its high moisture content and the fact that it is distributed around a multitude of small mills. It is estimated that worldwide there are about 4000 boilers fired with bagasse [12].

In the northern hemisphere harvesting lasts for 6 months and begins early in November, while in Australia the crushing season lasts from mid-June to mid-December. Since the sugar content of the cut cane falls rapidly, it must be processed within 24 h of being harvested. The stalks are crushed to squeeze out the sugar-containing juice, and then washed with a small amount of water to leach out as much sugar as possible. The spent cane is burned to provide power for the mill.

## The Properties of Bagasse

During the crushing of the cane to extract the sugar-laden juice from the bulk fibre, the residue is sprayed with water to wash out as much sugar as possible, without excessively diluting the juice. As a result 2–3% of the mass of the bagasse is sugar, and the moisture content is consistently in the range 48–52%. The ash content varies, mostly due to harvesting practices and weather conditions. After rain soil tends to be splashed onto the stalks, and the ash content rises. Values between 1 and 5% (dry basis) are generally experienced.

A typical elemental analysis of bagasse (dry ash-free) is given below:

B. R. Stanmore formerly with University of Queensland.

B. R. Stanmore (✉)
University of Queensland, Brisbane, QLD, Australia
e-mail: b.stanmore@uq.edu.au

| | |
|---|---|
| Carbon | 48% |
| Hydrogen | 5 |
| Nitrogen | 1 |
| Oxygen (by difference) | 46 |

The material has a fibrous morphology, with a wide range of 'particle' sizes. The largest particles may be 100 mm in length and only 5 mm thick. On the basis of appearance, Cuban bagasse was separated by Ponce et al. [19] into two sub-fractions, A and B. The fibrous Fraction A had a high length-to-width ratio and originated mostly from the outer shell of the stalk. Fraction B had a significantly lower length-to-width ratio, and consisted mostly of spongy pith with little or no fibre content. Luo [14] showed that Fraction A contained more cellulose and less lignin than B.

The stringy physical shape makes the material cohesive and difficult to handle. The uncompacted bulk density is low at $\sim$120 kg m$^{-3}$, while individual particles from fraction A return dry densities of around 400 kg m$^{-3}$. For these reasons the feeding of bagasse into combustors is generally achieved by sending it down very steep chutes into a feed opening in the wall of the boiler where a jet of air blows it into the furnace interior. The introduction of swirl spreaders to give more even distribution can boost boiler steam output to 120% of nominal maximum rating (MCR) before operating problems arise [18].

The specific energy of 'pure' cellulose is about 17 MJ kg$^{-1}$ and that of 'pure' lignin about 27 MJ kg$^{-1}$. Since bagasse is a mixture of about 45% cellulose, 20% hemi-cellulose and 30% lignin, its dry SE is of the order of 19 MJ kg$^{-1}$. However as it contains around 50% moisture and some ash as-fired, the value in practice is reduced to 8–9 MJ kg$^{-1}$.

## Possible Methods for Increasing Energy Output

There is scope for modifying the harvesting and sugar extraction practices in order to generate power for export. The amount of energy present in the bagasse is more than enough to meet the mechanical and thermal demands of mill operation, such as crushing and the evaporation of juice to give crystals. This is achieved at the moment by burning the bagasse to generate steam in specially designed boilers. Only a few larger mills have been adapted to generate electrical power for export. A similar situation applies in the palm oil industry, where by-product 'fibre' is available for energy production [11].

### Harvesting

The leaves of the cane plant (known as 'trash'), represent an almost equal amount of energy as the bagasse. At the moment they are burned before harvest in some sugar economies, or are stripped and left on the field in others. Inclusion of this material into the bagasse stream will double the available quantity of energy. In this discussion the processing of trash can be assumed to follow the same route as bagasse.

### *Sugar Extraction*

In many mills, the crushing rollers and other machines are driven by small steam turbines. This makes economic sense if the bagasse has no other value and is burned to dispose of it. Australian mills operate at about 52% steam-on-cane (SOC) i.e. each tonne of cane processed will consume 520 kg of steam. Conversion to electric drives would reduce this figure to about 45% or less, thus freeing up some steam for export power generation. In the northern hemisphere where sugar is extracted from beet, the figure is 35% SOC, but a figure as low as this would be difficult to reach for cane processing.

The ubiquity of sugar plantations in tropical and sub-tropical climates means that a large resource of renewable energy is currently being handled. In contrast to purpose-built, dedicated biomass-based plants such as proposed in the literature, bagasse is already collected and transported to a process plant. No new planting, coppicing, harvesting or transporting facilities are required. This makes it a prime candidate for the adoption/extension of power generating capabilities.

The two routes to the generation of electricity from bagasse/trash are:

1. combustion in a boiler to generate steam which is then expanded in a turbine, and
2. gasification in a reactor with steam to produce a low energy fuel gas suitable for burning in a dedicated gas turbine.

## Combustion of Bagasse to Generate Electrical Power

Traditional power generation via steam is based on the Rankine cycle, in which high pressure/temperature steam passes through an expansion device such as a turbine to extract energy and drive an electrical generator, see Fig. 1. The thermodynamics of the cycle are shown in the accompanying temperature–entropy (T–s) diagram. For process use, medium pressure steam may be extracted partway down the expansion step to be used as a heating medium, and the remainder of the steam sent to the condenser after further expansion. In most systems the final expansion is to sub-atmospheric pressures in order to extract as much energy as possible. The partial expansion system is designated as an extracting turbine and the latter

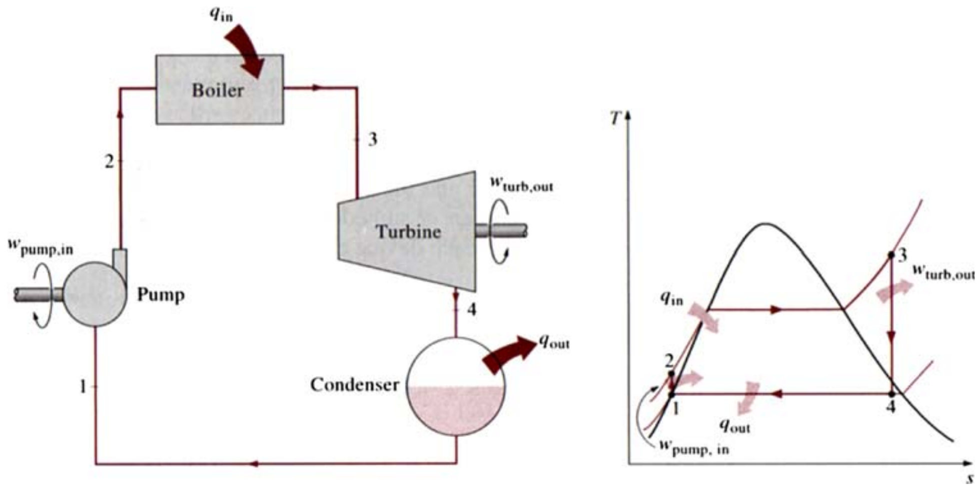



**Fig. 1** Simple Rankine cycle [7]

as a condensing unit. A heat source such as a boiler burning a suitable fuel (fossil or biomass) powers the cycle.

Steam is generated in the water-walls of the furnace and then superheated in heat exchangers arranged across the gas exit passage. Water circulation from the steam drum is generally by natural convection. The adiabatic flame temperature of moist bagasse at 40% excess air is around 1250°C, and at 80% excess (a typical figure for older-style boilers) is around 1050°C. These potential flame temperatures are not as high as produced by most fossil fuels, so that lower temperature steam is generally produced. Superheating is necessary to avoid excessive condensation in the turbine, which would lead to damage of the blades.

The boiler efficiency is defined as the ratio of enthalpy in the product steam to the chemical enthalpy in the bagasse fuel. An optimisation undertaken by Barroso et al. [4] considers a standard bagasse fuel having a specific energy as-fired of 7.74 MJ $kg^{-1}$ burned in a typical Cuban boiler under various operating conditions. The results in terms of steam load and excess air are presented in Fig. 2. A value around 80% can be anticipated in practice. The remaining 20% of the fuel enthalpy is lost to the atmosphere in the hot fluegases and in parasitic energy demands of the boiler.

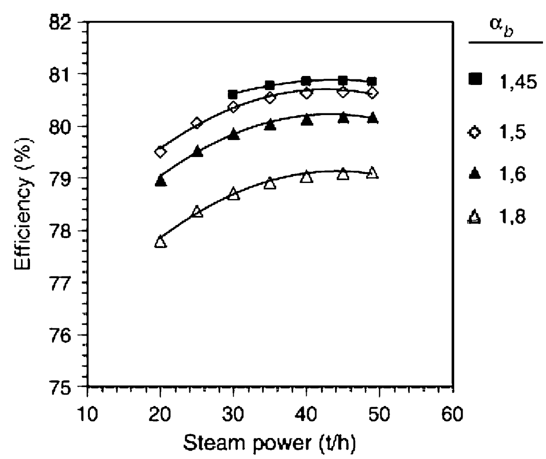



**Fig. 2** Boiler efficiency against load and stoichiometric air ratio $\alpha_b$ [4]

## Steam cycles

The two efficiencies reported for thermal power generation are those for the boiler alone, and the overall conversion to electricity. As noted above, the former is the ratio of the heat extracted into the steam to the chemical energy in the fuel. The latter is the ratio of electrical output of the installation to the chemical energy in the fuel, and is equal to $w_{turb,out}/q_{in}$ in Fig. 1 (less losses in the alternator). It should take into account energy used in the generation unit for the operation of fans, pumps, conveyors, gas cleaning equipment and general power demand. Most of the energy in the fuel is rejected as $q_{out}$ (Fig. 1) in the condenser, so that the overall efficiency from current technology is less than 20%.

An efficient system suitable for process applications is an extraction or passout turbine where sufficient medium pressure steam for plant use is extracted, and the remainder is further expanded to sub-atmospheric pressures. Because of the demand for medium pressure steam in the operation of a sugar mill, many systems expand only to 3–4 bar (135–145°C saturation) and send the outlet steam to the crystallisers. The change in enthalpy of the inlet steam in passing through the turbine blades is converted into electrical energy at around 70% efficiency. Most of the enthalpy is still present in the outlet steam so that the electrical output is minimal (as it is not the main aim of the process).

Since the theoretical efficiency of a steam cycle is determined by the Carnot temperatures, operating efficiencies have traditionally been low. Old style low pressure/low temperature steam units (1.8 MPa/220°C) would

give an overall efficiency of 10–12%. The thermodynamics of a steam cycle condensing at 35°C under these conditions is depicted on a temperature-entropy (T–s) chart as Cycle A on Fig. 3. In this calculation, an isentropic efficiency of 70% is assumed for the turbine.

A modern unit operating at 3.7 MPa and 400°C is capable of 84% boiler efficiency [27], but only 13% electrical with a condensing steam turbine during the crushing season. In the off-season, when all the steam is available for power generation, the theoretical electrical efficiency of this cycle relative to the superheated steam enthalpy is about 24% (Cycle B on Fig. 3). Taking the furnace efficiency and other losses into account, the overall electrical efficiency i.e. relative to the fuel enthalpy is around 17%.

A comprehensive study of power generation under Australian conditions was carried out by a Queensland consortium, see Dixon et al. [9], and summarised by Stanmore et al. [24]. It was found that a cycle raising steam at 6 MPa and 480°C would deliver net efficiencies of 13% during the crushing season when some process steam is required by the mill, and 20% during the off-season. The net power output was estimated to be 115 kWh electrical per tonne of cane. In practice during a verification test, a mill in La Réunion processed between 300 and 400 tph of cane and burned 120 tph of bagasse in the boilers [1]. The production of net power in this case was around 470 kWh per tonne of bagasse burned i.e. also around 115 kWh per tonne of cane. It should be noted that this is much less than the power obtained by burning a tonne of municipal solid waste.

Table 1 from Joyce and Dixon [12] shows details of various power generation systems, with typical operating temperatures, the equivalent Carnot efficiencies and the likely overall efficiencies for the different plant configurations. It includes biomass and fossil fuels, as well as advanced cycles and gasification plants. Modern coal-fired plant has an efficiency of about 38%, similar to that for a gas turbine plant. The highest efficiency is for a gas-fired combined cycle plant at 52%.

## Types of Firing Systems in Biomass Boilers

A combustion system for solids must be designed to give good contacting between the fuel and the combustion air, and then maintain the fuel at a high temperature until burnout is complete (sufficient residence time). The

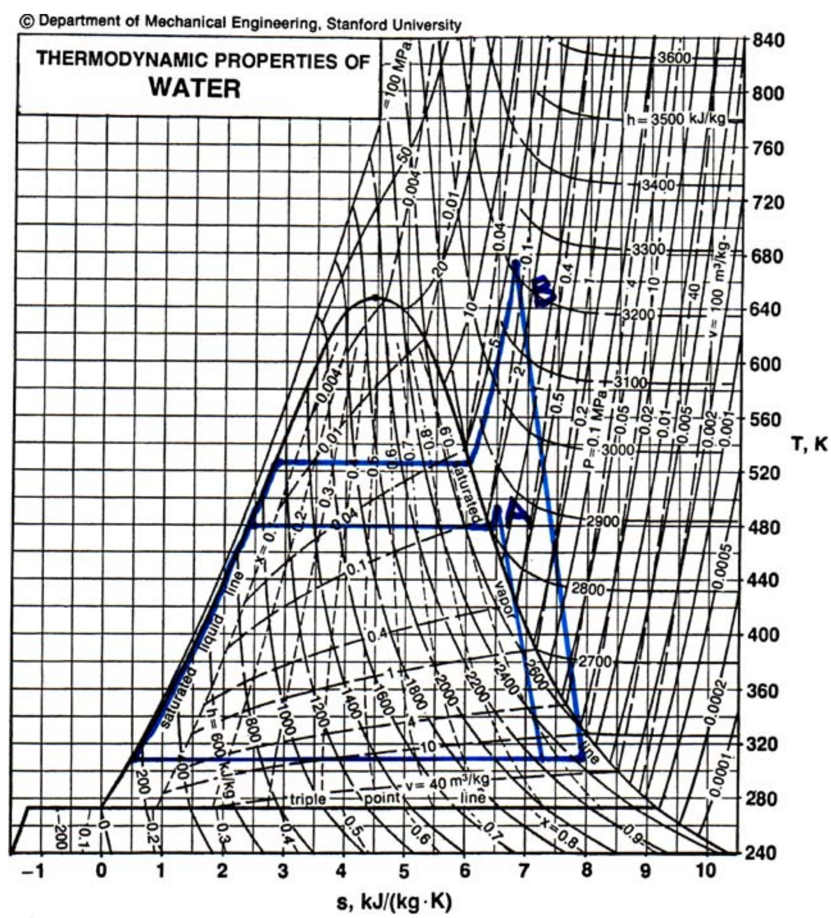



Fig. 3 The T–s chart for steam showing typical Rankine cycles for bagasse mills

**Table 1** Overall efficiencies of generation systems [12]

| | $T_H$ | $T_C$ | $\eta$ Carnot (%) | $\eta$ Typical (%) | % of Carnot eff. | $\eta$ Fuel basis (HHV) (%) |
|---|---|---|---|---|---|---|
| 18 Bar sugar factory power cycle (non-condensing 100% HP steam to generator) | 493 (220°C) | 388 (115°C) | 21.3 | 13.5 | 63 | 10 |
| Modern sugar factory cogen. plant (non-condensing) | 753 (480°C) | 398 (125°C) | 47.1 | 29.5 | 63 | 25 |
| Start of the art sugar factory cogen. plant (100% condensing mode) | 813 (540°C) | 311 (38°C) | 61.7 | 32.0 | 52 | 28 |
| Standard utility steam cycle (black coal) | 813 (540°C) | 311 (38°C) | 61.7 | 42 | 68 | 38 |
| Gas turbine (High efficiency unit in open cycle mode) | 1373 (1100°C) | 673 (400°C) | 51.0 | 35 | 69 | 37 |
| Advanced supercritical steam cycle (black coal) | 873 (600°C) | 311 (38°C) | 64.4 | 47 | 72 | 42 |
| Gas turbine combined cycle (natural gas—incl. heat recovery steam cycle hence two working fluids) | 1373 (1100°C) | 311 (38°C) | 77.3 | 53 | 69 | 52 |

combustion process involves the progressive drying and devolatilisation of the bagasse, leaving a char which is comprised mostly of carbon. Although the char may represent only 10% of the mass of the initial feed particle, it dominates the combustion process because of its longer burning time.

It has been shown that drying takes place by evaporation within a particle at a moisture front where the local temperature is at wet bulb conditions [23]. As a result, the drying process follows a logarithmic decline. Pyrolysis or devolatilisation does not commence until about half of the water has been removed, because the water vapour being driven off keeps the interior of the particle below the decomposition temperature. Volatiles i.e. gases and tars begin to appear at a temperature of 220°C and continue to evolve up to a temperature of 350–450°C [15, 22]. This process also follows a logarithmic decline. The composition of the volatiles relative to the original dry matter is roughly 25% gases (CO, $CO_2$, $CH_4$ etc.), ~20% water vapour and ~40% tar liquids [25].

The residual char (~10% of the dry matter) is mostly carbon, but retains any original mineral matter and some heterogeneous elements—oxygen, nitrogen etc. For instance, a bagasse sample containing 3.4% ash (dry basis) registered 12.1% ash in the char [15]. The nitrogen content of this char was 2.4% and the sulphur 0.3% dry ash-free. Char combustion occupies the major part of the residence time of particles in the boiler, and unburned carbon is to be avoided. For a bagasse particle 1 mm in diameter and 10 mm long with 50% moisture, the simulated times for drying, devolatilisation and combustion of the isolated particle under typical combustion conditions are 1, 2 and 150 s respectively. In an operating boiler these times are much longer due to the interactions with adjacent particles.

The main difficulty in burning bagasse is maintaining a stable flame during the combustion of such a wet fuel. To prevent flameouts, various techniques have been employed. The simplest system is a steel grate similar to that used with other solid fuels such as coal and wood. Both stationary and moving grates are in use to support a fuel bed through which combustion air, sometimes with preheat, is blown in an upwards direction. Other air is injected from above as overfire air in jets to complete the oxidation of volatiles. Stability is maintained by the large mass of fuel at various stages of the burning process being in close proximity. In all systems the fines tend to be blown out of the bed and burn in entrainment (suspension), while the larger particles remain on the grate. A radiative refractory arch above the entry section of the bed is commonly used to enhance drying and ignition.

With a moving or travelling chain grate, the bagasse is gravity-fed into spreaders which distribute the material across a slowly-moving grate formed from metal links. A large modern unit is pictured in Fig. 4 [27]. The furnace chamber formed from water tube walls is in the foreground, with the boiler drum and tubes behind, and the gas cleaning system at the rear. The grate is driven slowly towards the back of the furnace, so that sufficient residence time is available, and the ash falls off the rear.

With a stationary grate system the fuel is fed onto the perforated grate from a number of feeders across one wall

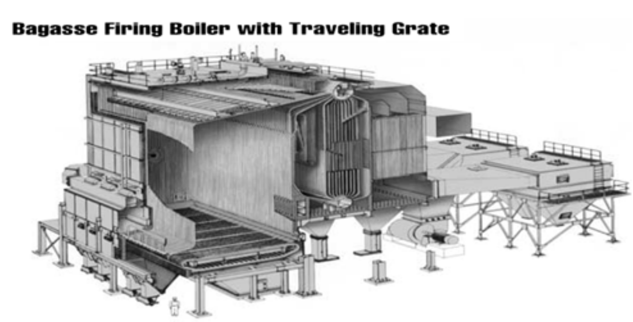



**Fig. 4** A large furnace installation firing bagasse to produce 120 tph of steam at 3.7 MPa and 400°C [27]

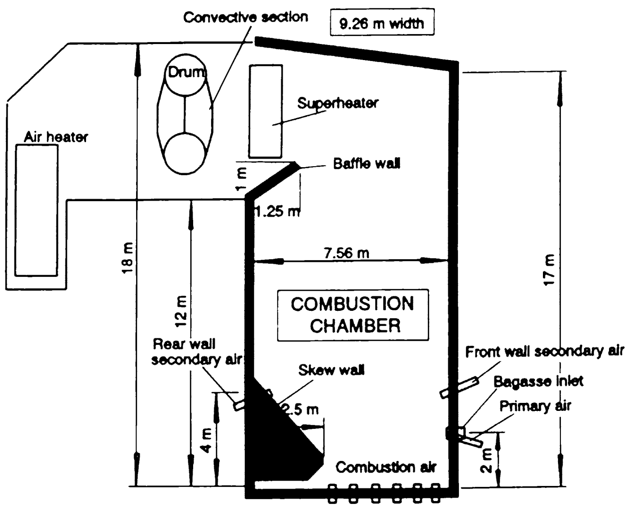



**Fig. 5** Section through a Queensland boiler firing 60 tph of bagasse and generating 150 tph of steam at 1.75 MPa and 280°C [16]

of the furnace. The front-wall fired system in common use in Australia [16] and also in India [21] is a combined entrainment/stationary grate configuration in which the bagasse is fed through 5 or 6 feeding chutes on the front wall. On entry the bagasse streams are projected into the furnace by air jets. A diagrammatic section through such a furnace is shown in Fig. 5. Approximately 90% of the combustion air is sent through the grate, and the remainder is supplied as feed air (5%) and overfire air (5%). The grate consists of rows of 52 mm diameter holes on 500 mm centres across the furnace floor.

On the rear wall is located a large refractory heat sink (marked 'skew wall' in Fig. 5). The wall serves two purposes: to direct the gas flow towards the front wall and to act as a thermal reservoir inside the furnace. The refractory mass is kept hot by the high combustion rates occurring just in front of it. A deficiency of this mode of stationary grate combustion is the behaviour of the larger particles, which initially do not burn but tend to build up on the grate. After a period of delay of the order of one minute, they ignite en-masse and send a pressure/composition pulse through the furnace [30].

A firing system which is standard for the combustion of Victorian brown coal, a very high moisture content fuel (65–70% as-fired), is corner-firing tangentially towards a horizontal circle in the centre of the furnace. This arrangement has greater flame stability because the four fuel streams impinge onto one another with a strong rotational motion. The system can be further stabilised by 'split' firing i.e. separating out a fuel-rich stream which is added in the lower part of the furnace, from a more dilute water-rich stream added higher up. Some CFD studies of the corner firing of bagasse by Luo et al. [17] indicate that heat output can be significantly enhanced over front wall firing for the same furnace volume. An increase of the order of 25% in output has been predicted. The study found that the orientation of air injection should be close to horizontal, and the velocity has little effect. This author does not know of any furnaces with this configuration currently burning bagasse, although it would provide much higher volumetric outputs than the standard designs.

A modern approach which is favoured for pulverised coal combustion is the swirl burner, in which a finely-divided fuel is fed into a preheated air stream with a strong rotational component induced via swirl vanes or blocks on the secondary air, as in Fig. 6. The swirl induces a low pressure central recirculation zone or CRZ, so that hot gas is drawn back into the entering fuel stream. This contact enhances ignition and stabilises the flame. A conical exit or quarl assists in forming a stable flame ball, see Fig 6. Larger particles penetrate further into the CRZ before being deflected

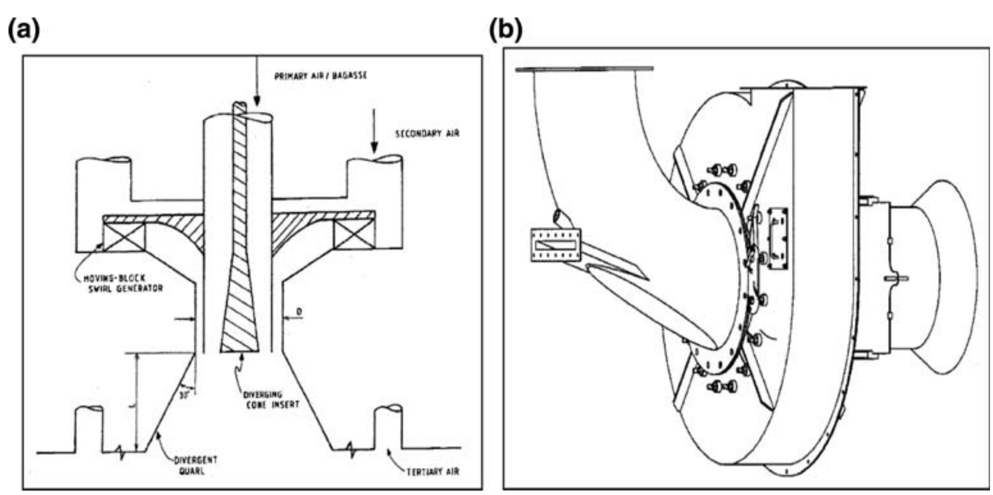



**Fig. 6** Swirl burner design applied to bagasse (**a**) Cross-section (**b**) Arrangement [10]

backwards and sideways by the return flow. The longer residence times at high temperatures promote heating, devolatilisation and burning. The system has been applied with success to bagasse combustion, although some drying of the feed is required [18]. A disadvantage of entrainment firing is that all the ash necessarily ends up in the flyash.

## Erosion, Corrosion and Fouling

The combustion of bagasse introduces some operating problems typical of biomass furnaces, caused by the action of ash particles entrained in the flue gas flow. When various forms of biomass were burned in a pilot furnace, Capablo et al. [6] found that the concentration of ash in the gas flow was proportional to the mineral matter content of the original fuel.

One of the problems is erosion of the water tubes, particularly of the superheaters which are suspended in the gas flow e.g. Fig. 5. Mann et al. [18] note that erosion is a significant contributor to the maintenance costs of bagasse boilers. Erosion occurs at positions where tubes experience a high local gas velocity, high particle concentrations and an obtuse impact angle. The usual solution is to install baffles to improve flow conditions. In most cases, visual examination of the flow configuration can identify where to locate baffles and what shape to install. In difficult i.e. complex cases, the study of erosion can be carried out by means of computational fluid dynamics or CFD [10].

Related to tube erosion is the process of air-heater corrosion, in which the heat transfer tubes corrode on the fluegas side. Examination of offending heaters by CFD simulation has shown that due to uneven flow distribution, some areas of the tube surface can be over one hundred degrees below fluegas temperature, and closer to inlet air temperature [18]. In fluegases containing high moisture contents as with bagasse, the temperature can fall below the wet bulb value, so that condensation of water vapour leads to the observed corrosion. Once again the solution is better management of the gas flow.

A third operational problem is fouling of the superheater tubes, brought about by the ash particles being partly melted so that they adhere to the tube surface. This has the effect of blanketing the surface area and lowering the heat transfer rates. Biomass such as bagasse contains high levels of the alkali metals potassium and sodium, which form chlorides and silicates with low melting points. These form a thin, sticky initial coating on the tubes to which other ash particles can adhere. In this way a thick deposit can form.

Figure 7 from Zhou et al. [31] presents the effect of fouling on a sample superheater tube placed in the fluegas stream of a boiler burning straw. The three graphs depict the measured values of fluegas temperature, deposit mass and heat transfer rate. As the ash deposit builds, the heat transfer flux rapidly falls from an initial figure for the clean tube of 70 kW $m^{-2}$ to a steady state value around 25 kW $m^{-2}$. The continuous black lines represent the output of a predictive model for the growth and shedding of the deposit.

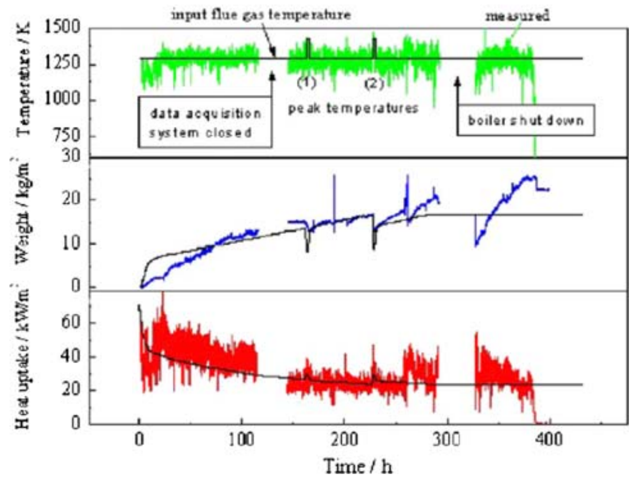



**Fig. 7** The progress of fouling on a superheater tube in a straw-fired furnace. *Top*: Gas temperature. *Middle*: deposit mass. *Bottom*: Heat flux [31]

## The emission of pollutants

Particulate removal for biomass ash is relatively simple. Older mills tended to use inertial separation such as multiclones, or alternatively wet scrubbers. Modern installations can produce emission levels of <10 mg $Nm^{-3}$ [1]. Ash from biomass fuels tends to behave well in electrostatic precipitators, resulting in high collection efficiencies.

Sulphur dioxide concentrations from modern units located on the island of La Réunion are typically in the range of 35–70 mg $Nm^{-3}$ (12–24 ppm) at 6% oxygen (Anon), which is far lower than would be anticipated from the sulphur content of the bagasse ($\sim$0.4%).

It is difficult to predict the $NO_x$ concentration, as this is a function of a number of interacting factors including fuel properties and combustion conditions. The values of nitric oxide measured at the two plants on La Réunion were between 380 and 470 mg $Nm^{-3}$ (280–350 ppm), also @ 6% $O_2$. These values are typical of those reported by Werther et al. [28] for biomass combustion, and are higher than values for a coal with a similar nitrogen content. Werther attributes this to the fact that most of the nitrogen is lost as volatiles, and readily enters into the complex nitrogen gas-phase chemistry to produce NO. The high value of excess air employed for bagasse combustion favours the process. Another reason is the small amount of char formed, meaning that there is little carbon available for the reduction of NO to $N_2$. However the low flame temperature minimises the generation of thermal $NO_x$.

Lower values of $NO_x$ are reported from a mill in Cuba by Teixeira and Lora [26]. In a boiler burning 10–12 tph of 50% moisture bagasse, they found that the emissions ranged between 100 and 160 mg $Nm^{-3}$ at 7% $O_2$. The major variable influencing the results was the amount of excess air.

Although the levels of levels of $SO_x$ and $NO_x$ in the fluegas may be elevated, it is rare for gas treatment systems to be installed in the rural areas where cane is grown. Low-$NO_x$ burners have been developed for coal combustion, but the simple technology and low volume of production of bagasse boilers has not given any incentive to manufacturers to improve their design.

Ramjeawon [20] undertook a life-cycle analysis for the generation of power from sugar cane on the island of Mauritius. The basis for comparison was the generation of 1 GWh of electricity from bagasse, as compared to its generation from imported coal. The bagasse option performs well in the areas of greenhouse gas emissions, acidification, and non-renewable energy inputs, but performs poorly in relation to water consumption and eutrophication.

## Gasification of Bagasse to Generate Electrical Power

The term gasification is used to describe the partial oxidation of carbonaceous matter to produce a fuel gas mixture containing some combustible gases such as carbon monoxide, hydrogen, methane and other hydrocarbons. The advantage of the gasifying process is that a difficult solid fuel, i.e. wet, fibrous bagasse, is converted into a readily handled and easily burned fuel gas. The second advantage is that higher conversion efficiencies can be obtained, see Table 1. A plot of plant efficiency against size for three options, viz steam cycle, gasifier + gas engine and a combined cycle plant or IGCC as presented

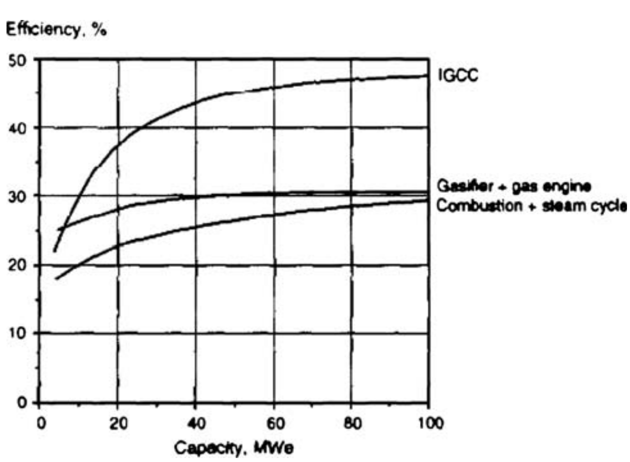



**Fig. 8** The efficiency of power generation from biomass [5]

by Bridgewater is reproduced in Fig. 8. The efficiency values, which are for a generalised biomass, are higher than quoted in the sections following, but show the same relativities.

The reaction gases to produce oxidation may be oxygen, steam or carbon dioxide, or a mixture of these. The reaction of carbon with oxygen is exothermic, and those with $CO_2$ and $H_2O$ are endothermic. There are 5 gaseous species commonly considered for gasification reactions: $H_2$, CO, $CO_2$, $H_2O$ and $CH_4$. The reactions of four species which attack carbon are:

| | | $\Delta H°$ | Relative reaction rate (800 K and 0.1 atm) |
|---|---|---|---|
| R1 | $C + O_2 \leftrightarrow CO_2$ | $-395$ kJ $mol^{-1}$ | $10^5$ |
| R2 | $C + H_2O \leftrightarrow CO + H_2$ | +132 | 3 |
| R3 | $C + CO_2 \leftrightarrow 2\,CO$ | +173 | 1 |
| R4 | $C + 2\,H_2 \leftrightarrow CH_4$ | $-75$ | $3 \times 10^{-3}$ |

The reaction with oxygen is orders of magnitude more rapid than the endothermic ones, so that the latter dictate gasifier design. The overall process can be autothermal i.e. self-sustaining, if the exothermic and endothermic rates of reaction are balanced to maintain a constant temperature. This is achieved by adjusting the relative flowrates of the feed gases. A common approach is to use a mixture of oxygen and steam. When pure oxygen is used with steam, a high energy gas is produced viz 12–18 MJ $Nm^{-3}$. If air is used to supply the oxygen, the product is diluted with nitrogen, and the gas has a low specific energy ~5 MJ $Nm^{-3}$.

One significant effect which must be addressed is the tars formed by devolatilisation of biomass in the gasifier. These tars can easily foul the process vessels, as compressors, engines, turbines and even heat exchangers demand very clean gas. Together with ash particulates and alkali metals, tar presents a significant gas cleaning problem. Of the various strategies which have been to considered remove them, high temperature filters and tar crackers are commonly proposed.

The type of contacting between solid fuel and reactant gas determines the configuration of any gasifier. Large solid chunks, as with wood or coal, allow simple moving beds to be utilised, with either co- or counter-current gas flow. The finer size and fibrous morphology of a biomass like bagasse dictate either entrainment or fluidised bed contacting. On the large scale, the overwhelming choice is the circulating fluidised bed, which permits long residence times to ensure complete conversion. As a result, the technology must be more substantial and complex than some small units currently being used for wood wastes. A

good summary of the technology and associated problems, now somewhat dated, is given by Bridgewater [5].

Two system configurations are possible with the application of gasification to power generation. The simplest is the close-coupled gasification/combustion configuration where the product gas from the gasifier is immediately transferred to a boiler and burned to raise steam for a Rankine cycle. The efficiency is lower than for the alternative IGCC described below, but the need for hot gas cleanup is eliminated.

The second more sophisticated approach to using product gas is the generation of power from the cleaned biogas in either a reciprocating engine or a rotating turbine. It is generally accepted that at the smaller scale (<10 $MW_e$) engines are more suitable. However gen-sets are available up to 50 $MW_e$, and gas turbines have been developed to burn low-energy landfill gas at sizes down to 3 $MW_e$. Bridgewater notes "Engines have the advantage of robustness, high efficiency at small sizes, higher tolerance to contaminants than turbines (e.g. up to 30 ppm tars), easier maintenance and wide acceptability. However, operation in combined-cycle mode is rarely justified, as only a small increment in efficiency can be gained. There is poor economy of scale, as capacity is a function more of the number of cylinders than their size, and constant specific capital costs that are independent of size are typical".

A more efficient approach extracts heat from the burned gas in two stages, and is known as the integrated gasification combined cycle (IGCC). In this combination, the cleaned gas from the gasifier is burned in a gas turbine at temperatures around 1000–1200°C, and then after expansion the lower temperature (700–800°C) reject heat is used for steam-raising in a Rankine cycle. The exhaust gases are passed through a heat exchanger/boiler to raise steam for the smaller steam turbine, and the two generating units form a 'combined' cycle. The system, although more expensive, offers much higher conversion efficiencies than a simple steam cycle, see Table 1.

The flowsheet for a pressurised combined cycle plant using bagasse/trash as fuel which was proposed for application in Queensland is depicted in Fig. 9. The product gas from the gasifier is cooled by sending it to a dryer for incoming feed and then to a preheater for feed water. After hot gas cleanup it is sent to a stand-alone combustion chamber attached to the gas turbine. The hot exhaust gas from the expansion turbine is used to generate high pressure steam as part of the conventional boiler at the mill, and then sent to the stack. High pressure air for the gasifier is bled from the compressor of the gas turbine.

At the moment no IGCC plant is operating on bagasse, but a similar plant was run on Refuse-Derived Fuel (RDF) by TPS Termiska in Italy. In this plant the air-blown, atmospheric pressure fluidised bed gasifier is followed by a second fluidised bed in which tars are destroyed. A moist fuel like bagasse offers one advantage because when the material is dried, the water released can be retained in the

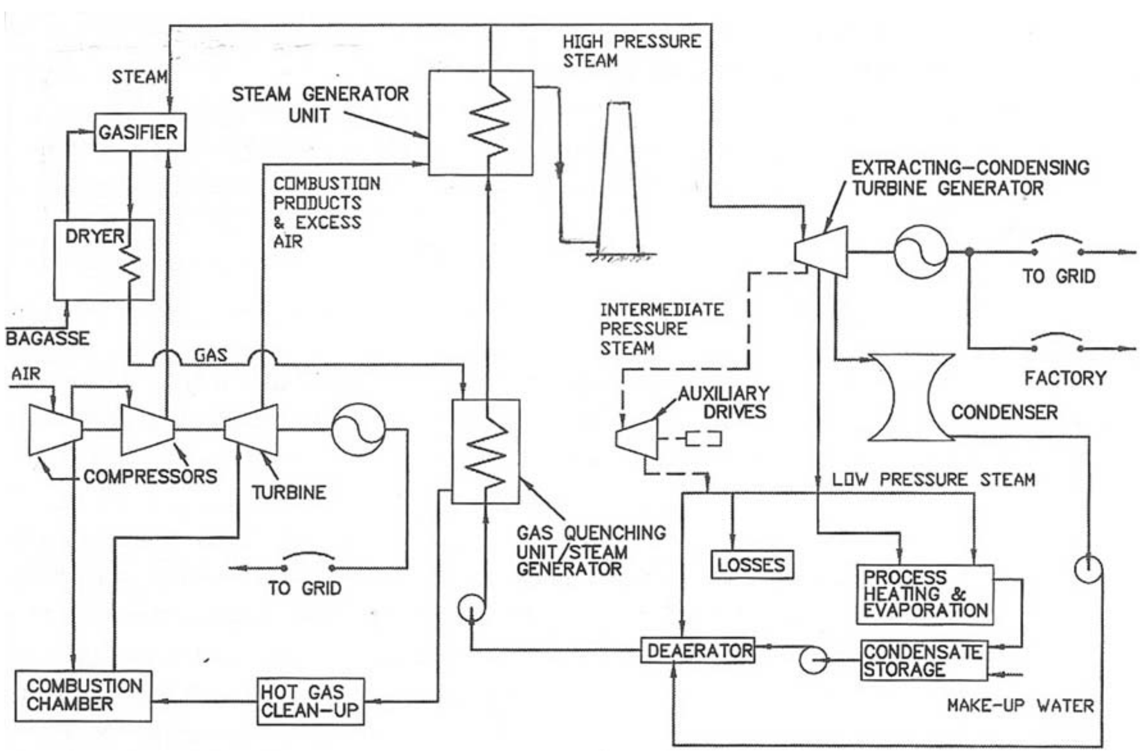
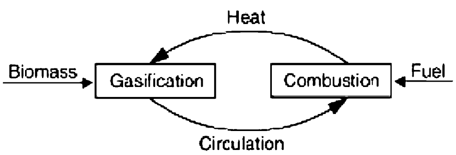



**Fig. 9** Flowsheet proposed for a pressured IGCC plant designed for bagasse gasification [9]

feed stream and hence participate in the gasification process, becoming part of the working fluid in the gas turbine.

Even though gas turbines have been developed to handle low energy gases (5 MJ $Nm^{-3}$), it is desirable to generate a fuel gas with as high an energy content as possible. If air is used as the oxidant, the product gas is dominantly nitrogen. However, eliminating this has traditionally required an expensive oxygen separation plant. This dilemma can be overcome by using two fluidised beds, one for gasification and the other for oxidation of the char. The scheme is depicted in the following




and the process configuration is shown in Fig. 10 [5]. Heat is supplied to the system by burning the char (sometimes with supplementary fuel) in air in the fluidised bed combustor, from which the fluegas is vented to atmosphere. The hot char/ash is sent to the fluidised bed gasifier, into which the biomass is fed together with steam to cause gasification. The product gases have a high energy content as they are not diluted with nitrogen. Char/solids from the gasifier are then sent back to the combustor for reheating, and thus circulate between the beds.

An advanced IGCC demonstration unit has been developed by the Technical University of Vienna in association with Repotec. Located at Güssing in Austria, it is a two stage unpressurised, fluidised unit using woodchips as feed [2]. The solids in the gasifying vessel are catalytically active in cracking tars, and circulate with the char. The output of 2 $MW_e$ is generated by a gas engine at an estimated efficiency of 37%; in addition, 4.5 $MW_t$ is available as process heat. The high reliability of the system has been demonstrated over some years. A model of the behaviour of the gasifier has been developed by Kaushal et al. [13]. A process similar in technology and size is under development by Batelle in Vermont in the USA.

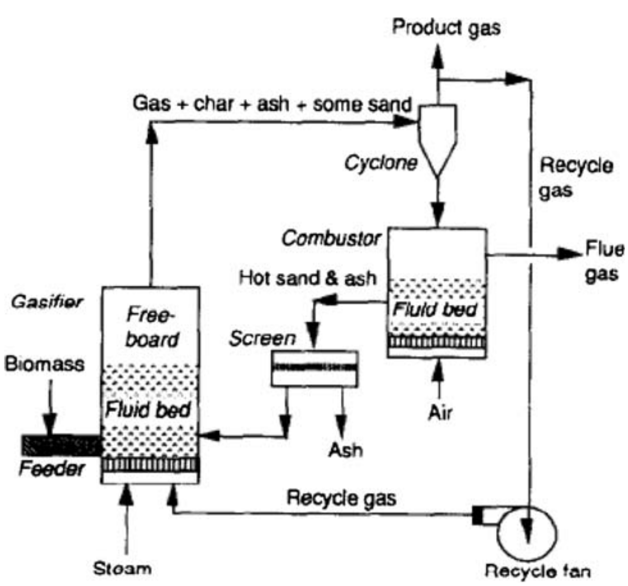



**Fig. 10** Schematic of dual bed gasification system with separate gasifier and combustor vessels [5]

It is operationally and thermodynamically advantageous to carry out gasification processes at elevated pressures. Operationally, high pressures mean smaller and cheaper process vessels, but the main advantage is that downstream compression of the product gas is not required in order to feed the gas turbine. Thermodynamically the production of higher specific energy products like methane is favoured by increased pressure (Reaction R4 above). The complications introduced by high pressures (e.g. 2 MPa) are solids feeding and hot gas cleanup. Feeding a difficult material such as bagasse into a pressure gasifier introduces significant handling problems above those encountered in simple boilers.

There has been limited development of bagasse gasification technology. The most significant investigation was a pilot scale Renugas® unit operated by the University of Hawaii in the 1990s [3]. The pressurised, fluidised bed unit operated at a nominal 100 t/day. Its performance was bedevilled by problems in feeding the bagasse against >2 MPa internal pressure. The properties of the product gas from the operation at 855°C and 2300 kPa are given in the following table. The composition is similar to the product gas from other biomass gasification processes.

| | |
|---|---|
| Hydrogen | 7.3% (v/v) |
| Oxygen | 0.05 |
| Nitrogen | 37.2 |
| Carbon monoxide | 10.6 |
| Carbon dioxide | 14.6 |
| Water | 23.0 |
| Methane | 7.0 |
| Higher h'carbons | 0.33 |
| Specific energy (MJ/$Nm^3$) | 5.1 |

The Australian consortium mentioned above estimated the output from a combined cycle plant with the gas turbine operating at 1200°C and the steam cycle as before [24]. The analysis found that the net efficiencies were 30% in the crushing season and 38% in the maintenance season. The power generated was 260 and 295 kWh per tonne of cane respectively.

A summary of the situation in 2005 is given by Babu [2] as follows. "Despite the widely acknowledged benefits, commercialisation of BMG (biomass gasification) has

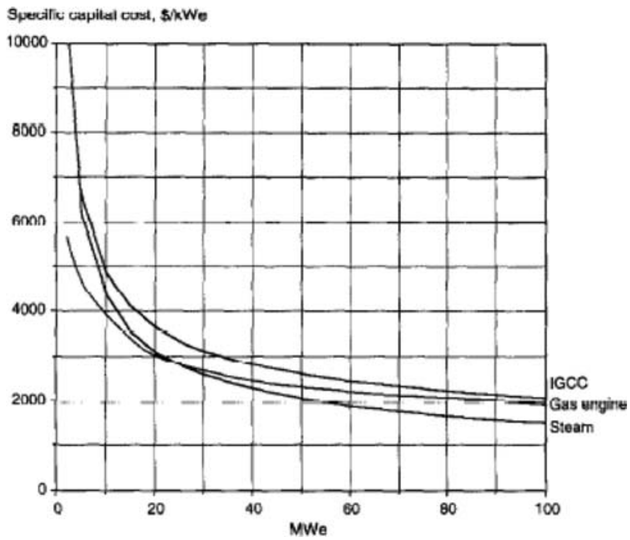



**Fig. 11** Specific capital cost against plant size [5]

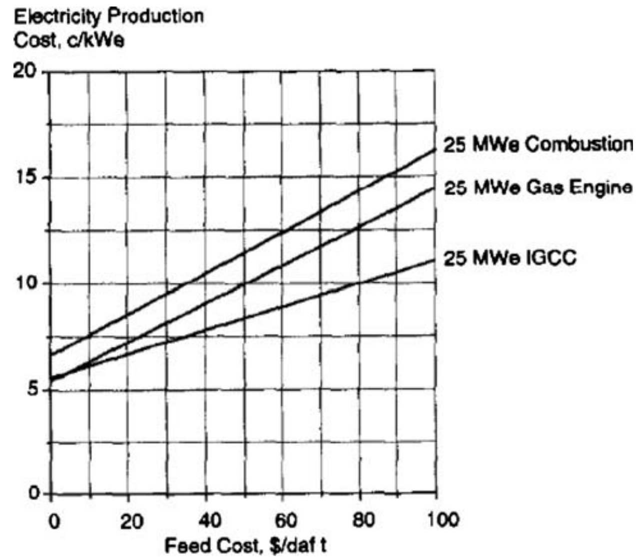



**Fig. 12** Estimated cost of generated power against feed cost at 25 $MW_e$ scale [5]

fallen short of expectations. The reasons include absence of market pull due to competition from conventional fuels, inadequate government policies and incentives for BMG projects, lack of infrastructure for quality controlled feedstock supply at a guaranteed price, and the inability to obtain performance guarantees by many technology developers".

## The cost of electricity from bagasse

Costs of power generation from biomass have been presented by a number of authors e.g. Bridgewater [5], Bain et al. [3]. The paper by Bridgewater documents the situation as in it applied in 1994. There is a strong dependence of capital cost on size, Fig. 11, with gasification systems costing around \$2000 per $kW_e$ at 100 $MW_e$ size. Simple steam plant is listed at \$ 1500 per $kW_e$. There is little difference in cost of generated power between steam cycles and BMG with either engine or turbine, so the comparative simplicity and mature technology of the steam cycle is an advantage. The only incentive to develop gasification is as a result of its higher cycle efficiency. Similarly, the cost of generated electricity is only cheaper for IGCC when fuel is costed at >\$20 per tonne at 6–7¢ per kWh, see Fig. 12. (Note that the units of the y axis should be ¢ per kWh, not ¢/$kW_e$). Where IGCC gains an advantage is when fuel cost is high, as the combined cycle has superior efficiency.

A somewhat later report by the US National Renewable Energy Laboratory [8] examined the economics of BIGCC in the US context. The results for various configurations are reproduced in Table 2. The capital costs are lower than given by Bridgewater, but the cost of power is comparable. The value of the wood feed was set at \$ 42 per tonne.

The study by the Australian consortium estimated conversion costs, based on the operation of a mill processing 600 tph of cane [24]. The calculations were done for 3696 h during the crushing season and 2400 h in the off-season.

**Table 2** Economic analysis of BIGCC systems [8]

Summary of results

| | High pressure direct gasifier, aero-derivative gas turbine | High pressure direct gasifier, greenfield plant | High pressure direct gasifier, advanced utility gas turbine | Low pressure indirectly-heated gasifier, advanced utility gas turbine | Low-pressure direct gasifier, advanced utility gas turbine |
|---|---|---|---|---|---|
| Output (MWe) | 56 | 56 | 132 | 122 | 105 |
| Efficiency(%, HHV) | 36.01 | 36 01 | 39.70 | 35.40 | 37.90 |
| Capital cost (TCR, \$/kW) | \$1,558 | \$1,696 | \$1,371 | 51.108 | 51.350 |
| Operating cost incl. fuel (\$1,000/yr) | \$13,433 | \$13,675 | \$28,702 | \$27,983 | \$23,442 |
| COE (e/k Wh, current \$) | 7.91 | 8.20 | 6.99 | 6.55 | 7.03 |
| COE (e/kwh, constant S) | 6.10 | 6.31 | 5.39 | 5.11 | 5.43 |

Costs were included for plant modification to run at 45% SOC. At that time the best estimate of capital cost for IGCC was probably A$ 2000 per $kW_e$ (1998 Australian currency) at a nominal 200 $MW_e$ size. Consequently it was consistent with the figures given by Bridgewater [5] and Bain et al. [3].

The capital cost for conventional bagasse-fired steam plant in Australia was estimated to be A$ 1050 per $kW_e$, and this difference in capital cost with respect to BMG was reflected in the cost of generated power. Generation costs were estimated to be 4.2 A¢/kWh for an upgraded steam cycle, which was only slightly higher than that quoted for a coal-fired unit at that time. The estimated generated cost for the IGCC plant was significantly higher at 6.1 A¢/kWh in 1998 currency. In contrast, Fig. 12 shows IGCC to be cheaper at all scales, but this was not reflected in the Australian survey. The comparison between the two studies shows equality in power cost at the lower end of the fuel cost range in Fig. 12, where bagasse is regarded as a by-product. In view of the additional costs for development and proving of BMG to commercial status, it would be prudent to allocate higher generation costs over conventional steam cycles.

## Conclusion

The quantity and availability of bagasse worldwide makes it a suitable feedstock for additional power generation over the current output. Combustion systems for bagasse are commercial over a wide range of sizes, and there has been a steady increase in steam conditions to raise overall efficiency. With regard to gasification, the difficulties enumerated by Babu appear to have deterred development of its application to biomass. The fuel supply is guaranteed in the sugar industry, but the other problems he mentions still apply. Slow progress is being made in scaling up systems for forest wastes, but bagasse does not appear to be considered. The electricity production cost for BMG is probably greater than that for simple steam cycles, which represents a major disincentive to pursue gasification technology.

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